

Gravitational Wave Standard Candles

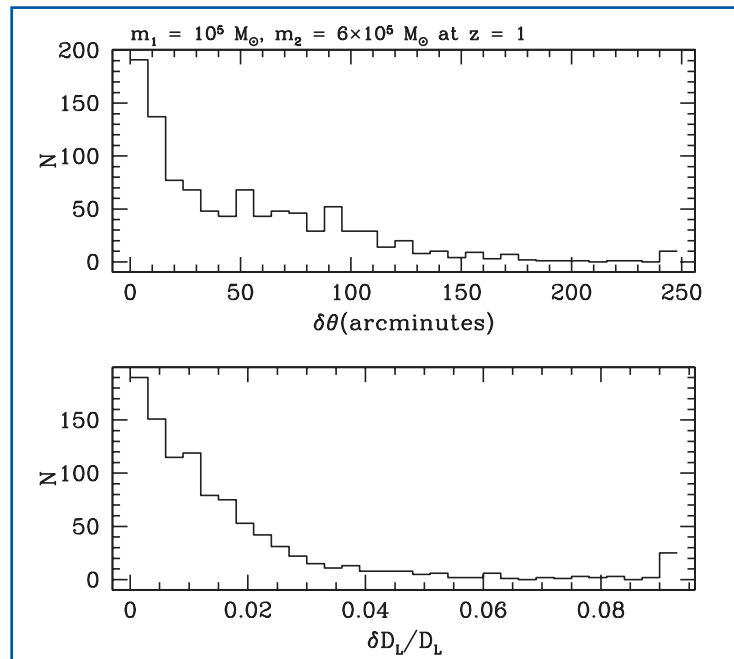
Daniel E. Holz (T-6), and Scott A. Hughes
(Massachusetts Institute of Technology);
abc@lanl.gov

One of the major challenges of cosmology for the foreseeable future is to understand the “dark energy,” the mysterious component responsible for the apparent accelerating expansion of our universe. One of our best observational probes of the dark energy is the distance-redshift relation, which maps the expansion history of the universe. Much of our knowledge of this relation comes from observations of distant Type Ia supernovae (SNe). Type Ia SNe are excellent standard candles, with a (calibrated) peak brightness thought to be known to about 15%. A possible objection to SNe as standard candles is the absence of a solid theoretical underpinning. Of particular concern is the possibility of evolution in SN brightnesses, leading to unknown systematic errors. In a recent paper [1], we discuss a completely independent standard candle: the gravitational-wave- (GW-) driven inspiral of massive binary black holes (BBHs).

Massive BBH coalescences are among the most luminous events in the universe. That luminosity (peaked at 10^{57} ergs/sec) is radiated almost entirely in GWs, which couple very weakly to matter. The planned space-based GW detector LISA (the *Laser Interferometer Space Antenna*) will be sensitive to these BBH waves from binaries with total masses $\sim 10^3$ – 10^6 solar masses, out to redshifts of at least $z \sim 5$ – 10 , and possibly beyond. Because BBH systems are relatively simple and well modeled (at least in the early “inspiral” phase of their coalescence), the GWs they generate determine the source’s luminosity distance with high accuracy: typically $\sim 1\%$ errors, with most of the uncertainty arising from correlations with pointing errors. BBH merger events will follow the mergers of galaxies and pregalactic structures at high redshift, and though the merger rate is poorly understood, LISA is expected to measure at least several events over its mission.

Although GWs provide an exceptional measure of luminosity distance, they do not provide a redshift to the source. This is a reflection of the scale-free nature of gravity. Thus BBH GW measurements alone do not probe the distance-redshift relation. However, as first noted by Bernard Schutz, should some kind of “electromagnetic” (EM) counterpart

Figure 1—
The distribution of position errors (top panel) and distance errors (bottom panel) for a gravitational-wave measurement of a representative supermassive binary-black hole merger at redshift $z = 1$. The position is generally known to within ~ 30 arcmin, while the distance accuracy is generally better than 1%.



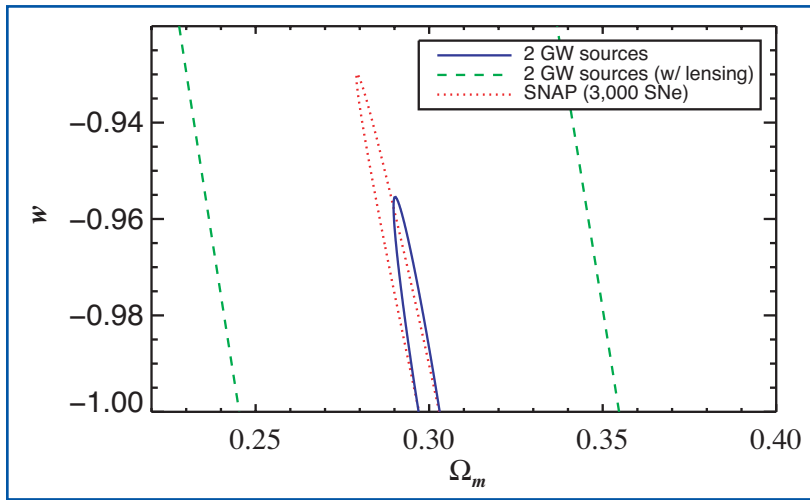


Figure 2—
Likelihood contours for measurement of the matter density, Ω_m , and dark energy equation of state parameter, w (with the pressure and density of the dark energy related by $p=w\rho$). This is for a flat universe, with $\Omega_m=0.3$ and $w=-1$. The two GW standard candle sources are at $z=1$ and $z=3$, while the SNAP supernovae are evenly distributed within $0.7 < z < 1.7$.

to a BBH GW event be identified, the situation is dramatically improved. By determining the source position, many correlations that set the distance error are broken. GW observatories are essentially all-sky. Although this enables detection of sources anywhere in the universe, it also means that detected sources are poorly localized. Even for the best-measured BBH GW events, the positional error boxes will be scarcely better than ~ 10 arcmin. Should an EM counterpart be identified in this box, however, the distance error then drops immensely—to better than 1/2% in many cases. In addition, an EM counterpart could enable determination of the source's redshift. A BBH GW source coupled with an EM counterpart would therefore constitute an extraordinarily good standard candle, far exceeding supernovae as distance indicators. To date, however, there has not been a great deal of careful analysis regarding the nature of the EM counterparts that might accompany a GW event. It is unlikely that such tremendously energetic events are completely dark in all other forms of radiation. Recent work indicates that there may be a jet directly assorted with the merger, or a counterpart months to years later due to delayed accretion.

In practice, gravitational lensing will limit the quality of this candle. GWs are lensed by intervening matter exactly as electromagnetic waves are lensed. As the waves propagate through our inhomogeneous universe, they

are magnified (or demagnified), inducing some error in our inferred luminosity distance to the source. The distribution of errors is such that a BBH candle will most likely end up being comparable in quality to Type Ia SNe. In other words, supernovae are already as good as they need to be. Gravitational lensing uncertainties are lurking just below the supernovae intrinsic uncertainties. However—and this is to be emphasized—the BBH GW candle will have entirely different systematics from SNe. Concordance between the two types of measurement could thus alleviate concerns about evolutionary effects in Type Ia SNe, and greatly increase one's confidence in all standard candles.

The gravitational waves from supermassive binary black-hole coalescence could very well be the absolute best cosmological standard candle (or, more appropriately, standard siren) that nature has to offer. However, gravitational lensing severely compromises their utility, and renders them little better than supernovae as cosmological markers.

[1] D.E. Holz and S.A. Hughes, "Using Gravitational-Wave 'Standard Sirens,'" Los Alamos National Laboratory report LA-UR-04-8603 (2004) (submitted to *Astrophys. J.*)

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